

# Air Shower Measurements with the LOPES Radio Antenna Array

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## Abstract

LOPES is set up at the location of the KASCADE-Grande extensive air shower experiment in Karlsruhe, Germany and aims to measure and investigate radio pulses from Extensive Air Showers. Since radio waves suffer very little attenuation, radio measurements allow the detection of very distant or highly inclined showers. These waves can be recorded day and night, and provide a bolometric measure of the leptonic shower component. LOPES is designed as a digital radio interferometer using high bandwidths and fast data processing and profits from the reconstructed air shower observables of KASCADE-Grande. The LOPES antennas are absolutely amplitude calibrated allowing to reconstruct the electric field strength which can be compared with predictions from detailed Monte Carlo simulations. We report about the analysis of correlations present in the radio signals measured by the LOPES 30 antenna array. Additionally, LOPES operates antennas of a different type (LOPES<sup>STAR</sup>) which are optimized for an application at the Pierre Auger Observatory. Status, recent results of the data analysis and further perspectives of LOPES and the possible large scale application of this new detection technique are discussed.

*Key words:* radio emission, air showers, ultra-high energy cosmic rays

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## 1. Introduction

The traditional method to study extensive air showers (EAS), which are generated by high-energy cosmic rays entering the Earth's atmosphere, is to measure the secondary particles with sufficiently large particle detector arrays. In general these measurements provide only immediate information on the status of the air shower cascade on the particular observation level. This hampers the determination of the properties of the EAS inducing primary as compared to methods like the observation of Cherenkov and fluorescence light, which provide also some information on the longitudinal EAS development, thus enabling a more reliable access to the intended information [1].

In order to reduce the statistical and systematic uncertainties of the detection and reconstruction of EAS, especially with respect to the detection of cosmic particles of highest energies, there is a current methodical discussion on new detection techniques. Due to technical restrictions in past times the radio emission accompanying cosmic ray air showers was a somewhat neglected EAS feature. For a review on the early investigations of the radio emission in EAS in the 60ties see [2]. However, the study of this EAS component has experienced a revival by recent activities, in particular by the LOPES project, and the CODALEMA experiment in France [3].

The main goal of the investigations in Karlsruhe in the frame of LOPES is the understanding of the shower radio emission in the primary energy range of  $10^{16}$  eV to  $10^{18}$  eV. I.e., to investigate in detail the correlation of the measured field strength with the shower parameters, in particular the orientation of the shower axis (geomagnetic angle, azimuth angle, zenith angle), the position of the observer (lateral extension and polarization of the radio signal), and the energy and mass (electron and muon number) of the primary particle. Another goal of LOPES is the optimization of the hardware (antenna design and electronics) for a large scale application of the detection technique including a self-trigger mechanism for a stand-alone radio operation [4].

Finally, within the frame of LOPES a detailed Monte-Carlo simulation program package is developed. The emission mechanism utilized in the REAS code (see [5] and references therein) is embedded in the scheme of coherent geosynchrotron radiation. Progress in theory and simulation of the radio emission in air showers is described in a further contribution to this conference [6].

The present contribution sketches briefly recent results of the LOPES project [7] obtained by analyzing the correlations of radio data with shower parameters reconstructed by KASCADE-Grande [8,9]. Hence, LOPES, which is designed as digital radio interferometer using large bandwidths and fast data processing, profits from the reconstructed air shower observables of KASCADE-Grande.

## 2. General layout, calibration, and data processing

### 2.1. General layout

The basic idea of the LOPES (= LOFAR prototype station) project was to build an array of relatively simple, quasi-omnidirectional dipole antennas, where the received waves are digitized and sent to a central computer. This combines the advantages of low-gain antennas, such as the large field of view, with those of high-gain antennas, like the high sensitivity and good background suppression. With LOPES it is possible to store the received data stream for a certain period of time, i.e. after a detection of a transient phenomenon like an air shower a beam in the desired direction can be formed in retrospect. To demonstrate the capability to measure air showers with such antennas, LOPES is built-up at the air shower experiment KASCADE-Grande [8]. KASCADE-Grande is an extension of the multi-detector setup KASCADE [9] (Karlsruhe Shower Core and Array DEtector) built in Germany, measuring the charged particles of air showers in the primary energy range of 100 TeV to 1 EeV with high precision due to the detection of the electromagnetic and the muonic shower component separately with independent detector systems. Hence, on the one hand LOPES profits from the reconstructed air shower observables of KASCADE-Grande, but on the other hand since radio emission arises from different phases of the EAS development, LOPES also provides complementary information and helps to understand the observables measured with the particle detector arrays of KASCADE-Grande.

In the current (2007 and 2008) status LOPES [10] operate 30 short dipole radio antennas (LOPES 30) and 10 logarithmic periodic dipole antennas (LOPES<sup>STAR</sup>). The latter operate in both polarization directions each (i.e. 20 channels), and are used for the development of a radio self-trigger system (see ref. [4]).

The LOPES 30 antennas, positioned within or close to the original KASCADE array (fig. 1), operate in the frequency range of 40 – 80 MHz and are aligned in east-west direction, i.e. they are sensitive to the linear east-west polarized component of the radiation only, which can be easily changed into the opposite polarization by turning the antennas. The layout provides the possibility for, e.g. a detailed investigation of the lateral extension of the radio signal as LOPES 30 has a maximum baseline of approximately 260 m. The read out window for each antenna is 0.8 ms wide, centered around the trigger received from the KASCADE array. The sampling rate is 80 MHz. The shape of the antenna and their metal ground screen gives the highest sensitivity to the zenith and half sensitivity to a zenith angle of  $45^\circ$ , almost independent on the azimuth angle. The logical condition for the LOPES-trigger is a high multiplicity of fired stations of the KASCADE-Grande arrays. This corresponds to primary energies above  $\approx 10^{16}$  eV; such showers are detected at a rate of  $\approx 2$  per minute.

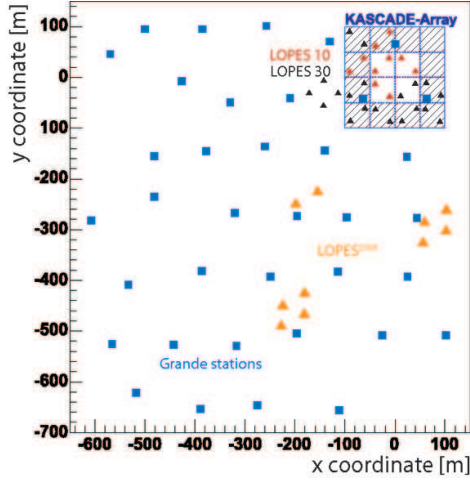


Fig. 1. Sketch of the KASCADE-Grande – LOPES experiments: The 16 clusters (12 with muon counters) of the KASCADE field array, the distribution of the 37 stations of the Grande array are shown. The location of the 30 LOPES radio antennas is also displayed as well as the positions of the 10 newly developed LOPES<sup>STAR</sup> antennas.

## 2.2. Amplitude calibration

Each single LOPES 30 radio antenna is absolute amplitude calibrated at its location inside the KASCADE-Array (end-to-end calibration) using a commercial reference antenna [11] of known electric field strength at a certain distance. The power to be received from the source in calibration mode is compared with the power recorded in the LOPES electronics. The calibration procedure leads to frequency dependent amplification factors representing the complete system behavior (antenna, cables, electronics) in the environment of the KASCADE-Grande experiment (fig. 2). The calibration results in a spread for the amplification factors between different antennas of nearly one order of magnitude. The obtained correction factors are applied to the measured signal strengths resulting in the true electric field strength which can be compared to simulated values.

Detailed investigations of possible sources of systematic uncertainties lead to a total uncertainty of  $\sigma_V/V = 70\%$  for the power (i.e.  $\sqrt{70\%}$  for the electric field) related amplification factor averaged over the effective frequency range. The main contribution is due to a systematic uncertainty in the field strength of the used reference source itself ( $\text{sys}_{\text{reference}} = 67\%$ ) as reported by the data sheet of the commercial antenna. Using another, more precisely calibrated reference radio source would improve this accuracy. The uncertainty of the calibration method itself ( $\text{sys}_{\text{calib}} = 20.5\%$ ) can be estimated from repeated measurement campaigns for a single antenna under all kinds of conditions. This total uncertainty also includes e.g. environmental effects, like those caused by different weather conditions present over the two years of calibration campaigns ( $\text{sys}_{\text{env}} = 13\%$ ) (fig. 3). The systematic uncertainty  $\text{sys}_{\text{calib}}$  of the calibration procedure has two additional sources: Electronic modules are temperature dependent

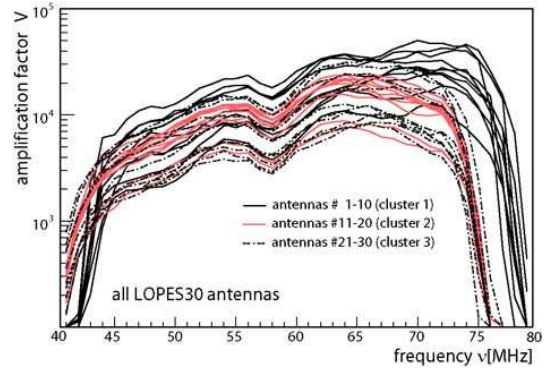


Fig. 2. Frequency dependent amplification factors for all 30 antennas obtained by the amplitude calibration [11].

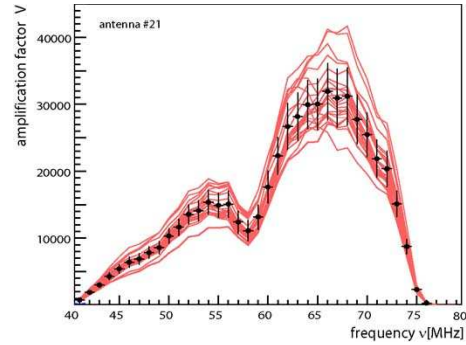


Fig. 3. Amplification factors (in linear scale) of one LOPES antenna for independent measurements. These measurements were spread over the course of nearly two years [11].

and we have shown that there is a relation between air temperature and amplification factor  $V(\nu)$  for the LOPES antenna system. A more precise correlation analysis and following correction can improve the overall precision for measuring electric field strengths. The antenna gain simulation contributes with large amount (15%) to the total uncertainty. In particular the simulation reveals a resonance at 58 MHz, where the measurements show that it is less pronounced and should be re-evaluated or interpolated in the gain calculations [11].

In addition, during LOPES measurements we place emphasis on the monitoring of the environmental conditions by measuring the static electric field and by recording parameters of nearby weather stations. Atmospheric conditions, in particular E-field variations during thunderstorms influence the radio emission during the shower development and the measurement of the radio pulses. By monitoring the environmental conditions, and comparing them with the antenna noise level as well as with the detected air shower radio signals, correlations will be investigated and corrected for.

An important conclusion is that the discussed strategy of calibration can be adapted for future radio antenna arrays measuring cosmic ray air showers. Especially at locations with much lower RFI an astronomical source, e.g. the galactic background radiation, can be used to cross-check the proposed amplitude calibration of a radio antenna system.

### 2.3. Data processing

The LOPES data processing includes several steps. First, the relative instrumental delays are corrected using a known TV transmitter visible in the data. End of 2007 this TV station was switched off, but could be replaced by a local dedicated source on site the Karlsruhe research center. The TV- as well as now the local source are also used for time calibration issues of LOPES. Next, the digital filtering, gain corrections and corrections of the trigger delays based on the known shower direction (from KASCADE-Grande) are applied and noisy antennas are flagged.

The geometrical delay (in addition to the instrumental delay corrections) by which the data is shifted, is the time difference of the pulse coming from the given direction to reach the position of the corresponding antenna compared to the reference position. This shift is done by multiplying a phase gradient in the frequency domain before transforming the data back to the time domain. This step includes the application of the calibration correction factors and also a correction for the azimuth and zenith dependence of the antenna gain.

To form the beam from the time shifted data, the data from each pair of antennas is multiplied time-bin by time-bin, the resulting values are averaged, and then the square root is taken while preserving the sign. We call this the cross-correlation beam or CC-beam.

The quantification of the radio parameters is by fitting the CC-beam pulse: Although the shape of the resulting pulse (CC-beam) is not really Gaussian, fitting a Gaussian to the smoothed data gives a robust value for the peak strength, which is defined as the height of this Gaussian. The error of the fit results gives also a first estimate of the uncertainty of this parameter. The finally obtained value  $\epsilon_{CC}$ , which is the measured amplitude divided by the effective bandwidth, is used for the analysis.

The analysis of the data using the CC-beam is based on the RFI cleaned raw data. However, the sampling of the data is done in the second Nyquist domain and a reconstruction of the original 40–80 MHz signal shape is needed to investigate the radio emission properties in more details. Therefore, an up-sampling of the data on a single antenna basis is performed (by the zero-padding method applied in the frequency domain) resulting in a band limited interpolation in the time domain [12] to reconstruct the original signal form between the sampled data points with 12.5 ns spacing. The method can be applied, because the needed information after sampling in the second Nyquist domain are contained in the stored data [13].

After applying the up-sampling and subtraction of an estimated noise level, the radio signals can be used to reconstruct the electric field strength in each individual antenna. By technical reasons, the CC-beam calculation could not been used on the up-sampled data at the time of this analysis. Therefore, for the following results up-sampling is only performed when signals in single antennas are discussed.

### 3. Results from the initial 10 LOPES antennas

First measurements (6 months data taking) were performed with a set up of 10 antennas (LOPES 10) with remarkable results [14]. With a sample asking for high quality events the proof-of-principle for detection of air showers in the radio frequency range was made [7]. In total, more than 600 events with a clear radio signal and with the shower core inside the KASCADE-Grande experiment could be detected. The analysis of these events concentrated on the correlations of the radio signal with shower parameters, in particular with the arrival direction and with the shower size, i.e. the primary energy of the shower.

The results support the expectation that the field strength increases by a power-law with an index close to one with the primary energy, i.e. that the received energy of the radio signal increases quadratically with the primary energy of the cosmic rays [10]. An index of this power-law close to one serve as a proof of the coherence of the radio emission during the shower development. A clear correlation was also found with the geomagnetic angle (angle between shower axis and geomagnetic field direction) which indicates a geomagnetic origin for the emission mechanisms.

Due to the geometrical layout of the KASCADE-Grande array (see fig. 1) the radio signal can be investigated for events which have distances up to 800 m from the center of the antenna setup. Investigating the average lateral behavior of the radio emission in more detail, a clear correlation of the signal strength with the mean distance of the shower axis to the antennas was found. By assuming an exponential function, the scaling parameter  $R_0$  resulted to  $230 \pm 51$  m [15].

Further interesting features of the radio emission in EAS were investigated with a sample of very inclined showers [16] and with a sample of events measured during thunderstorms [17]. The first one is of special interest for a large scale application of this detection technique, as due to the low attenuation in the atmosphere also very inclined showers can be detected with high efficiency. This is of great importance if ultrahigh energy neutrinos exist. With LOPES one could show that events above  $70^\circ$  zenith angle still emit a detectable radio signal. An update of this analysis is presented in ref. [18]. The latter sample is of interest to investigate the role of the atmospheric electric field in the emission process. LOPES data were recorded during thunderstorms, periods of heavy cloudiness and periods of cloudless weather. It was found that during thunderstorms the radio emission can be strongly enhanced, where no amplified pulses were found during periods of cloudless sky or heavy cloudiness, suggesting that the electric field effect for radio air shower measurements can be safely ignored during non-thunderstorm conditions [17].

## 4. Results of LOPES 30

### 4.1. Correlation with primary energy

The radio pulse height (CC-beam) measured by the 30 east-west polarized antennas of LOPES 30 can be parameterized as a function of the angle to the geomagnetic field, the zenith angle, the distance of the antennas to the air shower axis and an estimate of the primary particle energy calculated from KASCADE-Grande data [19]. The separated relations for the LOPES 30 events are displayed in figure 4. The fits to the geomagnetic angle, the distance to the shower axis, and to the primary energy are done separately and results in an analytical expression for the radio pulse height based on the estimated shower observables:

$$\epsilon_{\text{est}} = (11 \pm 1.) ((1.16 \pm 0.025) - \cos \alpha) \cos \theta \exp \left( \frac{-R_{\text{SA}}}{(236 \pm 81) \text{ m}} \right) \left( \frac{E_p}{10^{17} \text{ eV}} \right)^{(0.95 \pm 0.04)} \left[ \frac{\mu\text{V}}{\text{m MHz}} \right] \quad (1)$$

(With:  $\alpha$  the geomagnetic angle,  $\theta$  the zenith angle,  $R_{\text{SA}}$  the mean distance of the antennas to the shower axis, and  $E_p$  the primary particle energy. The given errors are the statistical errors from the fit.) One issue that has to be kept in mind is that this analysis is only made with the east-west polarized component, which can be the reason for the debatable  $1 - \cos \alpha$  dependence on the geomagnetic angle.

The analytical formula derived from LOPES measurements can be inverted and allows then an estimate of the primary particle energy from radio data. The combined statistical spread for the estimation of the energy of single events from LOPES data and KASCADE-Grande data is 27% for strong events. This is in the same range as the fluctuations in measurements with particle detector arrays alone.

### 4.2. Direction resolution

To investigate the capabilities of measuring radio signals in terms of direction estimates, we produce 4-dimensional radio images on time-scales of nanoseconds using the digital beam-forming [20]. We search this multi-dimensional parameter space for the direction of maximum coherence of the air shower radio signal and compare it to the direction provided by KASCADE. Each pixel of the image is calculated for three spatial dimensions and as a function of time. The third spatial dimension is obtained by calculating the beam focus for a range of curvature radii fitted to the signal wave front. We find that the direction of the emission maximum can change when optimizing the curvature radius. This dependence dominates the statistical uncertainty for the direction determination with LOPES. Furthermore, we find a tentative increase of the curvature radius to lower elevations, where the air showers pass through a larger atmospheric depth. The distribution of the offsets between the directions of both installations is found to decrease linearly

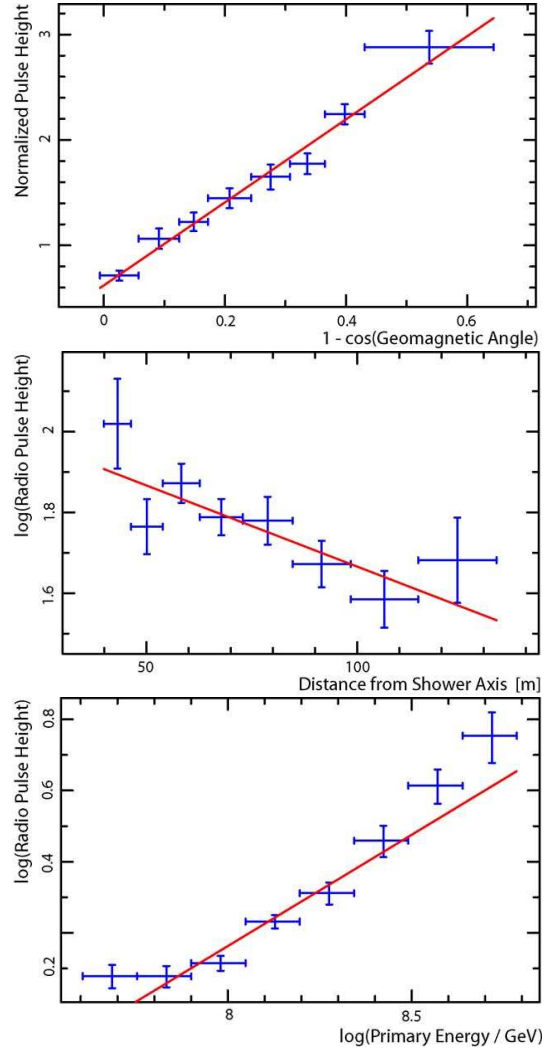


Fig. 4. Normalized radio pulse height plotted versus (from top to bottom): the angle to the geomagnetic field, the mean distance of the antennas to the shower axis, and the estimated primary particle energy [19]. The normalization is done by dividing by the fits to the other parameters (geomagnetic angle, distance, or energy).

with increasing signal-to-noise ratio (fig. 5). We conclude that the angular resolution of LOPES is sufficient to determine the direction which maximizes the observed electric field amplitude. However, the statistical uncertainty of the directions is not determined by the resolution of LOPES, but by the uncertainty of assuming a pure spheric wave. In addition, there are no systematic deviations between the directions determined from the radio signal and from the detected particles.

### 4.3. Frequency spectrum

The quality of the LOPES data allows us to study the spectral dependence of the radio emission from cosmic-ray air showers around 100 PeV. With a sample of 23 strong LOPES events, the radio spectrum received from cosmic-ray air showers in the east-west polarization direction over a frequency band of 40 MHz is analyzed. The radio data are

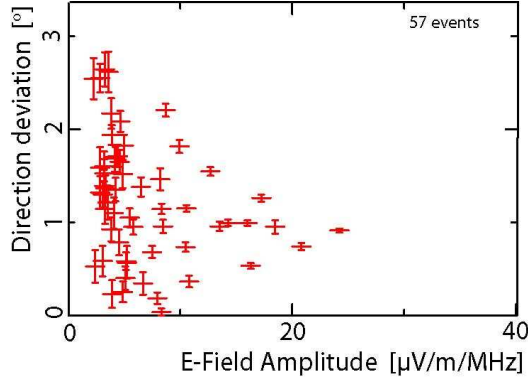


Fig. 5. Absolute angular separation between the LOPES and the KASCADE position as a function of electric field amplitude [20]. The statistical uncertainty in the direction of each event is plotted as an error bar.

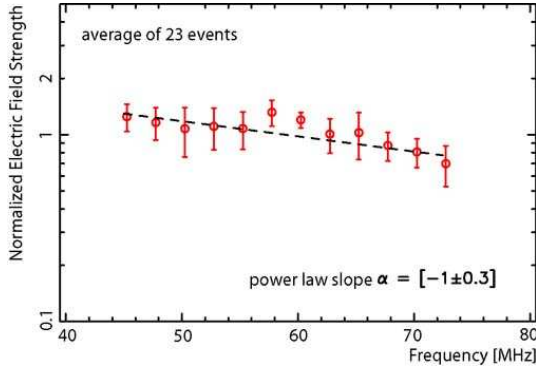


Fig. 6. Comparison of average cosmic-ray electric field spectra obtained with 23 LOPES events. The frequency bin values determined on the CC-beam are fitted with a power law function (dashed line) [21].

digitally beam-formed before the spectra are determined by sub-band filtering [21].

The resulting electric field spectra fall off to higher frequencies for all individual events. The spectral slopes of the selected sample of events depend on the length of the pulse, where longer pulses result in steeper spectra. However, the spectra do not show a significant dependence of the slope on the electric field amplitude, the azimuth angle, the zenith angle, the curvature radius, nor the average distance of the antennas to the shower core positions. The accuracy, with which the spectral amplitudes can be obtained, is limited by the instrument noise and phase uncertainties. Furthermore, the quality of the spectral slope is limited by the quality of the antenna gain model, which was simulated and measured in several calibration campaigns [11].

The average electric field spectrum of the 23 events can be fitted with an exponential function  $\epsilon_\nu = K \cdot \exp(\nu/\text{MHz}/\beta)$  and  $\beta = -0.017 \pm 0.004$ , or alternatively, with a power law  $\epsilon_\nu = K \cdot \nu^\alpha$  and a spectral index of  $\alpha = -1.0 \pm 0.3$  (fig. 6). The average slope of the spectra obtained with LOPES confirms basic expectations, but it is slightly steeper than the slope obtained from Monte Carlo simulations based on coherent geosynchrotron emission from fully parametrized air showers [21].

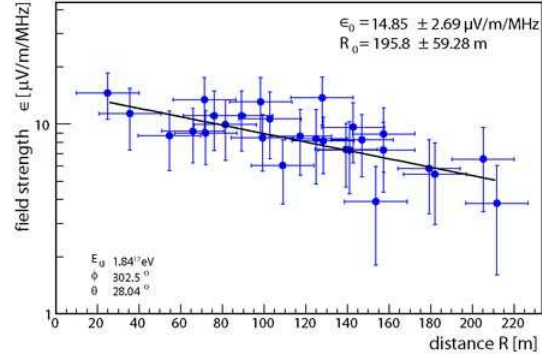


Fig. 7. Lateral distribution reconstructed from single antenna signal, shown for an individual shower [12].

#### 4.4. Lateral extension

For the analysis of lateral distributions of the radio emission in individual events 110 showers with a high signal-to-noise ratio were selected. Up-sampling is used to derive the electric field strength  $\epsilon$  for individual antennas. A background subtraction is performed based on a calculation using a time window (520 nanosecond width) before the actual radio pulse from the shower. The distance of the antennas to the shower axis is obtained with help of the reconstructed shower parameters from KASCADE-Grande. To investigate the lateral behavior of the radio signal an exponential function  $\epsilon = \epsilon_0 \cdot \exp(-R/R_0)$  was used to describe the measured field strengths. The fit contains two free parameters, where the scale parameter  $R_0$  describes the lateral profile and  $\epsilon_0$  the extrapolated field strength at the shower axis at observation level. An example of an individually measured event including the resulting lateral field strength function is shown in figure 7.

From the distribution of the obtained scale parameters (figure 8) one derives that the scale parameter peaks at  $R_0 \approx 125$  m and has a mean value of  $R_0 = 237$  m for the detected events. Here, the distribution comprises showers with an expected exponential decay as well as events with a very flat lateral distribution. Roughly 10% of the investigated showers show very flat lateral distributions with very large scale parameters.

The found lateral distributions with very flat lateral profiles are remarkable and require further investigations with higher statistics. The fact that we measured lateral distributions with a flat behavior towards the shower center or even over the whole observable distance range, can not be simply explained with instrumental effects.

Including the tail of the distribution in figure 8 the mean value agrees with the CC-beam based scale parameter in the parameterization of [19], whereas an exclusion of the tail obtains a scale parameter that agrees with the parameterization of [2].

A very important comparison for the understanding of the radio emission observed in EAS, the geosynchrotron radiation, was performed with detailed Monte Carlo simula-



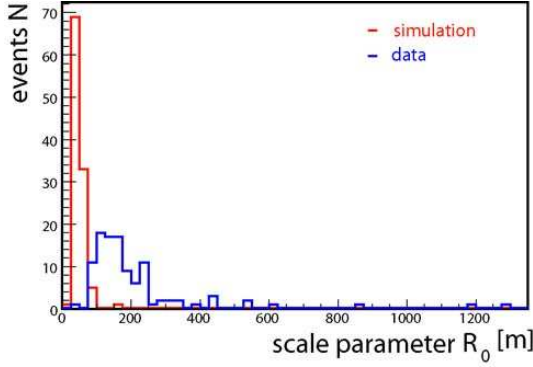


Fig. 8. Distribution of the scale parameter  $R_0$  obtained from measurements and simulations [12].

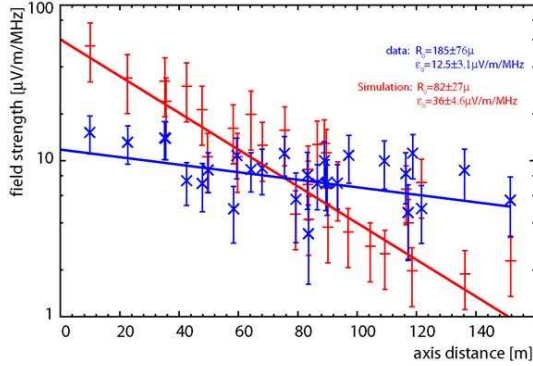


Fig. 9. Lateral distribution obtained for data (blue) and simulation (red) for an individual event [12].

tions on an event-to-event basis. This is now possible, due to the performed amplitude calibration of LOPES and the estimate of the field strength at individual antennas. It is as a basic necessity in order to get the absolute scale for the field strength. Due to a new simulation strategy, using more realistic air shower models with precise, multi-dimensional histograms derived from per-shower CORSIKA [22] simulations, detailed comparisons can be performed.

The REAS2 Monte Carlo simulation code (see [5,6] and references therein) is used to simulate the geosynchrotron radio emission for all the showers detected in the investigated data set. For each single event 250 showers were simulated with the fast one-dimensional shower simulation program CONEX, using the same values for the direction and the guessed primary energy under the assumption of a proton induced shower. The shower that represents the mean of all 250 simulated showers is selected. From the selected CONEX [23] shower the particle stack after the first interaction is used as input for a full CORSIKA simulation. The resulting information and the known shower core position is used in the REAS2 code to calculate the radio emission. The output are unlimited bandwidth pulses, that are digitally filtered with a rectangle filter from 43 to 76 MHz for the known antenna positions at ground, which can be directly compared with the measured lateral distribution (fig. 9).

The comparison of the distributions of the scale param-

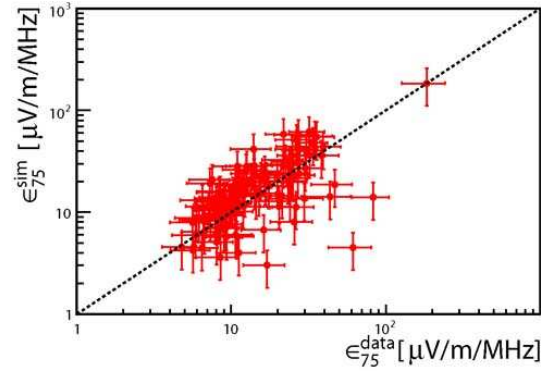


Fig. 10. Comparison of field strength at distance  $R$ . Correlations  $\epsilon_R^{\text{data}}$  obtained from measurements and  $\epsilon_R^{\text{sim}}$  obtained from simulation. The dashed line represents equal values from simulation and measurement [12].

ter from measurement and simulation is shown in figure 8. The mean for the distribution of the scale parameter from the simulation is  $R_0 = 50$  m. Such small values represent a steep lateral decrease of the field strength. In general the simulations give steeper lateral distributions. In addition, it was derived that the differences between measurements and simulations can be very large and that the unexpected very flat lateral profiles are never reproduced in simulations. In order to understand the underlying systematic effects significantly more statistics is needed.

The deviation in the scale parameters enters in systematically lower field strengths  $\epsilon_0^{\text{data}}$ , compared to the field strengths  $\epsilon_0^{\text{sim}}$  obtained from simulations at the shower center. The difference is a factor of three at the shower center. On the other hand we obtained at  $R = 75$  m a fairly good agreement between simulations and measurements (fig. 10) for all events. This is a promising result in itself, as such comparisons are performed for the first time for LOPES data.

#### 4.5. Polarization measurements

After one year of measurements of the east-west polarization component by all 30 antennas, the LOPES 30 set-up was reconfigured to perform dual-polarization measurements. Half of the antennas have been configured for measurements of the north-south polarization direction. By measuring at the same time both polarization components and by comparing with the expectations, the geosynchrotron effect as the dominant emission mechanism in air showers will be experimentally verified. First results on the analysis of these data are discussed in reference [24].

### 5. Large scale application: LOPES<sup>STAR</sup>

One of the main goals of the LOPES project is to pave the way for an application of this ‘re-discovered’ air shower detection technique in large UHECR experiments, like the Pierre Auger Observatory. Parallel to the measurements

at KASCADE-Grande LOPES follows this aim by optimizing the antenna design for an application at Auger, named LOPES<sup>STAR</sup> [4]. Going in direction of setting up a test array at Auger South, the possibilities of new antenna types and in particular, a self-triggering antenna system are also investigated. Meanwhile several dual polarized STAR-antennas are in operation at the KASCADE-Grande field (see fig. 1). Also by this system air showers could be detected. This information is used to optimize the self-trigger system of LOPES<sup>STAR</sup>. In parallel to the activities in Karlsruhe, also the first test set up with LOPES<sup>STAR</sup> antennas in Argentina at the Auger South experiment has detected first radio signals from extensive air-showers [25].

## 6. Summary

The main goals of the LOPES project are the investigation of the relation between the radio emission from extensive air showers with the properties of the primary particles and the development of a robust, autonomous, and self-triggering antenna set-up usable for large scale applications of the radio detection technique of air-showers.

With LOPES 30 we are able to follow the first goal of the LOPES project: The calibration of the radio emission in extensive air showers for primary energies below  $10^{18}$  eV. Because of the absolute amplitude calibration a direct comparison of the field strength with the expectations (simulations) is possible.

With LOPES the proof-of-principle for detection of cosmic particles by radio flashes from extensive air showers could be performed. First results obtained by correlating the observed radio field strength with the shower parameters obtained by the KASCADE measurements appear to be very promising for a more detailed understanding of the emission mechanism from atmospheric showers. Most interesting results are the found quadratic dependence of the radio-power on energy, the correlation of the radio field strength with the direction of the geomagnetic field, the exponential behavior of the lateral decrease of the field strength with a scaling parameter in the order of hundreds of meter, and that except during strong thunderstorms the radio signal is not strongly influenced by weather conditions. Large scaling radii allow us to measure the same field strength at larger distances from the shower core, which will be helpful for large scale applications of the radio detection technique. In particular, the quadratic dependence on energy will make radio detection a cost effective method for measuring the longitudinal development of air showers of the highest energy cosmic rays and cosmic neutrinos. This result places a strong supportive argument for the use of the radio technique to study the origin of high-energy cosmic rays.

LOPES is still running and continuously takes data in coincidence with the air shower experiment KASCADE-Grande. In this frame also improvements in the technology and the development of the self-trigger concept are tested.

Besides the experimental work done with the present antenna setup the LOPES project aims to improve the theoretical understanding of the radio emission in air showers. Supplementary emission processes like the Cherenkov-Askaryan-effect which plays the dominant role in dense media will be investigated.

The LOPES technology can be applied to existing cosmic ray experiments as well as to large digital radio telescopes like LOFAR and the SKA (square kilometer array), providing a large detection area for high energy cosmic rays. First approaches to use the technique at the Pierre Auger Observatory and at a first LOFAR station are under way.

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